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A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal

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Carbon dioxide removal is key to climate change mitigation, yet implications of its deployment remain unclear. Recent exponential growth in literature is rapidly filling this gap but makes the synthesis of the evidence on carbon dioxide removal side effects increasingly challenging. Here we address this issue by mapping this literature and proposing a taxonomy to synthesize and compare evidence on carbon dioxide removal side effects. The expansive evidence warrants the use of machine learning to systematically select relevant research and provide an inventory of nearly 400 co-benefits, challenges, and limits. We find rich evidence in Europe but little information for Africa, South America, and Oceania, where large-scale carbon dioxide removal is nevertheless projected. There is a predominance of articles discussing negative effects compared to positive ones. Starting from the limitations of our analysis and literature gaps, we provide entry points for future studies that can build on our literature-based taxonomy.

To comply with the Paris Agreement and to limit global warming to 1.5 °C, rapid and deep reductions in gross CO_2 emissions need to be complemented by active carbon dioxide removal (CDR) from the atmosphere[1–7]. CDR may contribute to climate change mitigation by accelerating the realization of net-zero CO_2 emissions, by offsetting residual emissions, which are often claimed to be hard to abate, and by eventually achieving net-negative emissions to reverse a potential temporary overshoot of the carbon budget[3,8,9] therewith gradually declining warming towards lower and safer levels[10]. Mitigation pathways for 1.5 °C warming—be they with no, limited, or high overshoot—therefore typically imply substantial amounts of CDR, although actual deployment rates vary as a function of policy choices[11–13].

CDR is continuously gaining attention and importance, partly due to ongoing delay in deep emission reductions but also as more and more net-zero pledges are being put forward. Most of the currently discussed CDR options, however, are not yet available at the scale required to substantially contribute to climate change mitigation[14,15]. While this implementation gap for CDR is already growing, there are also substantial environmental, socio-political, and economic implications arising from the deployment of CDR, which have not yet been sufficiently understood. Previous literature reviews have identified both benefits and risks of CDR deployment[16–22]. However, the CDR literature has been growing exponentially in recent years, which makes it increasingly challenging to comprehensively track and synthesize evidence on potential co-benefits, challenges, and limits[15]. In addition, the absence of a taxonomy to categorize and analyze evidence severely hampers the synthesis and comparability of knowledge.

We address this issue by systematically mapping the recent literature evidence on co-benefits, challenges, and limits for six land-based CDR options: afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, direct air capture with carbon capture and storage (DACCS), enhanced weathering (EW), and soil carbon sequestration (SCS). These options currently dominate the discussion on land-based CDR and are increasingly incorporated in integrated assessment models (IAMs) that are used to inform long-term mitigation strategies[11,12,15,23]. In this study, we consider accompanying or consequential effects of CDR deployment as well as phenomena hampering successful CDR deployment—details can be found in the Supplementary Note 2. These effects can be co-benefits, challenges, or limits of CDR deployment. In the following, we collectively refer to these effects as positive or negative side effects of CDR deployment.

We first show how the literature evidence on CDR side effects has evolved over time. Based on the recent literature, we present an initial taxonomy of CDR side effects across multiple categories and aggregation

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levels to provide a comprehensive overview of the literature evidence. We compare the literature-based effect profiles of the six considered CDR options and evaluate the available evidence regarding the desirability of the effects identified, that is, whether effects are associated with societal, environmental, and economic benefits or disbenefits. Ultimately, we explore geographic differences in the literature coverage and point towards potential literature gaps. More detailed information on the study's approach is provided under Methods.

Results

Overview of literature growth

We identified 982 peer-reviewed documents discussing side effects for the here-considered CDR options (Fig. 1a). The publication dates of these studies span across the last three decades, with steep growth in the number of published documents in recent years. More than 50% of these documents have been published since 2018 (Fig. 1b). We find a large variety in study designs and methodologies across studies, which can be categorized into five different study types. In recent years, the largest study type group was composed of quantitative analyses and modeling studies, including IAM studies, life cycle assessments (LCAs), and other quantitative approaches to estimate effect sizes across CDR options. A smaller group of studies is focused on qualitative analyses and conceptual deliberations, often focused on exploring policy implications and theoretical implementation challenges of CDR deployment.

Empirical evidence mostly comes from field experiments—often focused on soil-related implications of AR, biochar, and SCS—and partly from survey and interview studies, which often study the perception and acceptance of potential future CDR deployment. In addition to these original research studies, there is a group of documents composed of reviews and meta-studies, often focused on an individual side effect or CDR option.

Overview of side effects

Our literature inventory of CDR side effects in the full-texts selected for synthesis ($n = 233$) resulted in nearly 400 individual effects, covering a wide range of environmental, socio-political, technological, and economic aspects. These side effects were structured in a literature-based taxonomy for the six considered CDR options, grouped in three overarching effect spheres and spanning three levels of effect aggregation (Fig. 2). Each effect category is assigned a unique identifier to make the taxonomy easily operable and broadly applicable (Supplementary Fig. 2). The literature-based taxonomy is built on the peer-reviewed evidence for the six land-based CDR options considered in this study, including information on unspecific CDR as a general mitigation concept. Beyond direct side effects, the taxonomy also contains phenomena that impact successful CDR deployment.

Three overarching effect spheres were identified. The largest sphere covers a wide range of effects related to environmental and human health implications of CDR deployment. A second sphere includes the potential impacts of CDR deployment on economic prosperity and overall societal well-being. A third sphere entails a variety of potential implementation threats and challenges that may undermine the successful contribution of CDR to climate change mitigation. Generally, the spheres on environmental and human health, as well as on economic prosperity and societal well-being, primarily cover the direct side effects of actual or hypothesized future CDR deployment, while the sphere on implementation challenges mostly covers threats and barriers to successful CDR deployment. The literature-based taxonomy consists of 18 effect categories with several subcategory levels. An overview of these effect categories is given in Table 1.

Side effects per CDR option

For each included CDR option, we evaluated the option-specific coverage of side effects in the considered literature (Fig. 3). For none of the considered CDR options, the evaluated literature body provides information on all 18

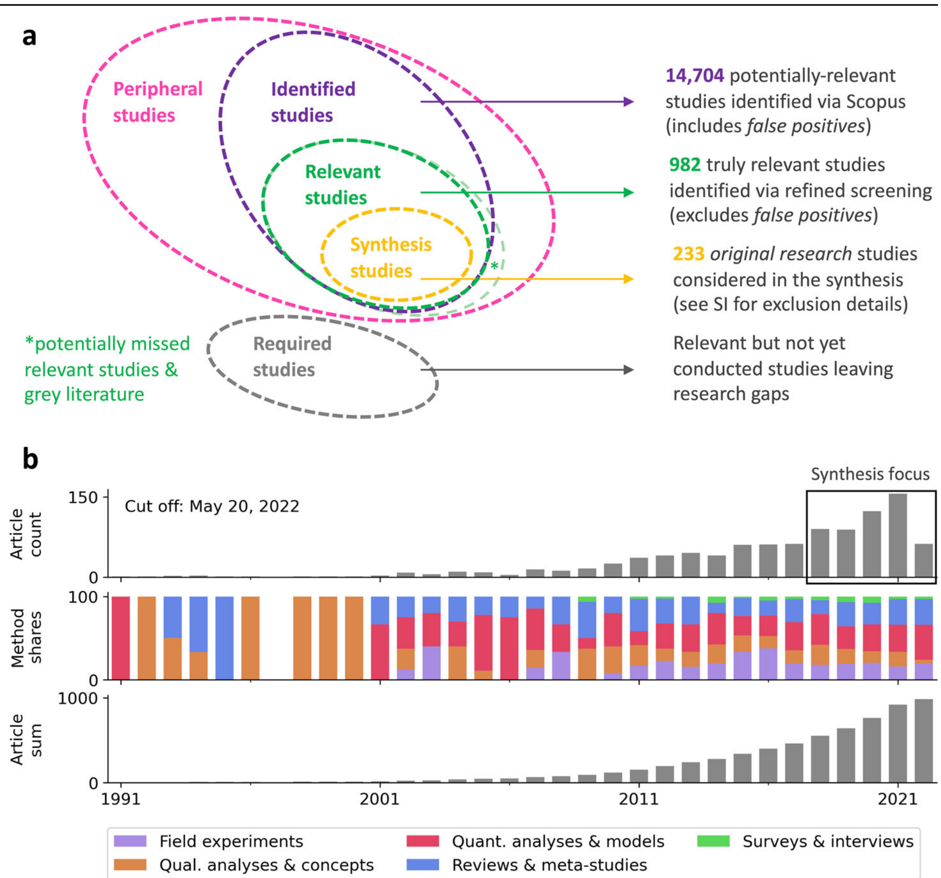

Fig. 1 | Overview of the CDR side effect literature evidence and its growth. a gives a stylized overview of the peripheral (at least remotely related), identified, relevant, and eventually synthesized literature evidence and how the different evidence components refer to each other. A detailed overview of the evidence identification, selection, and synthesis process is provided in the Methods section, as well as the Supplementary Note 1. **b** shows how the evidence on side effects has evolved over the course of the last three decades and gives an overview of the different study types in the set of relevant studies ($n = 982$).

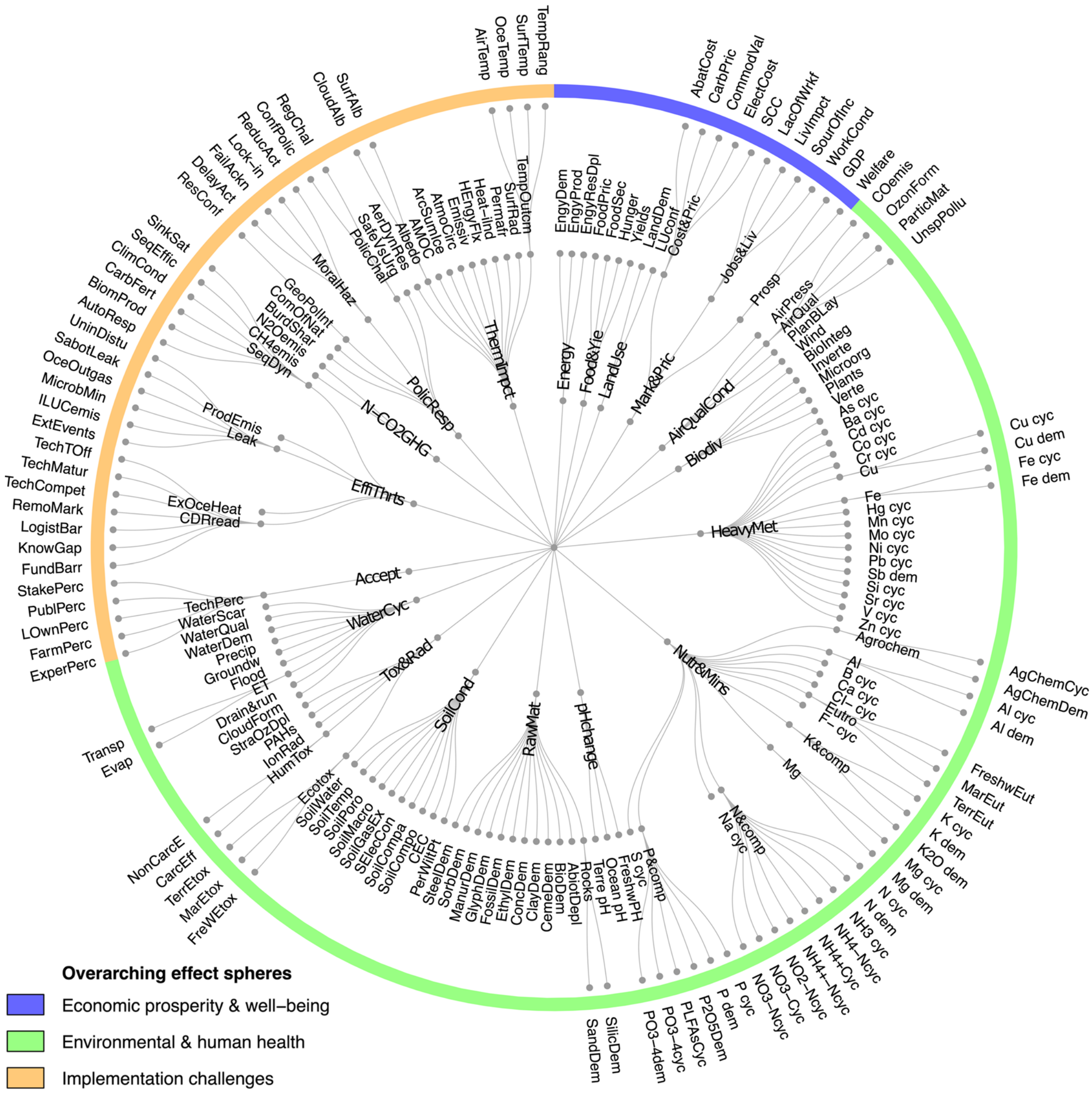

Fig. 2 | Literature-based taxonomy of CDR side effects. The taxonomy shows three levels of effect categories with higher levels of aggregation towards the center of the circular plot. Overarching effect spheres are shown in color, covering Economic prosperity & well-being, Environmental & human health, and Implementation challenges. An abbreviation list and unique identifiers for all effect categories are provided (Supplementary Tables 3, 4). This taxonomy is based on the synthesized literature information for AR, BECCS, Biochar, DACCS, EW, SCS, and option-unspecific CDR to provide an overview of relevant side effects of these CDR options. Not all categories are applicable to all CDR options. The here presented taxonomy reflects the recent literature evidence and is not conclusive, meaning that categories might evolve as new evidence arises.

effect categories. Between one and three effect categories are not available per CDR option, with many more subcategories either missing or not applicable. In each case, a careful assessment is needed of whether the effect does not occur for a particular CDR option or whether the missing subcategory points to an identified literature gap. The individual effect profiles and the level of detail of the available information vary considerably between the considered CDR options. Side effects of AR, biochar, and BECCS are well-covered by the literature, while information on DACCS and EW is more limited in terms of the number of articles and the spectrum of covered effects. The coverage of SCS ends up somewhere in the middle between the former and the latter group. The literature on option-unspecific CDR primarily deals with effects within the spheres of implementation challenges and economic prosperity and well-being, with less information on effects within the sphere of environmental and human health.

In addition to structuring the literature and identifying the coverage of individual side effects per CDR option, the analysis of the number of articles and the spectrum of covered effects per category is important to understand and synthesize the insights. Figure 4 shows, for each category, the number of evaluated articles focusing on positive and/or negative effects (desirability)—irrespective of effect sizes, significance, or study contexts.

AR: Changes to the water cycle, impacts on the flow of nutrients and minerals, biodiversity implications, soil changes, high land demand, and thermal impacts are among the most widely discussed side effects of AR. Slightly more evidence on negative ($n = 9$ articles) than positive ($n = 6$) implications for the water cycle are found, with some articles ($n = 6$) describing the effects of unclear impact. The impact desirability on nutrients in soils such as nitrogen, phosphorus, and potassium is mostly unclear due to context-dependency, with several articles indicating negative effects due to soil nutrient losses. The literature reports both positive and negative impacts on biodiversity with a small set of effects for which desirability is unclear. For several articles ($n = 8$), the desirability of effects on soils is unclear due to context-dependency, with a slight dominance of articles on positive ($n = 6$) compared to negative ($n = 4$) effects. Both positive and negative thermal impacts, mostly in terms of albedo changes, are reported for AR and strongly depend on the baseline conditions of the respective

Table 1 | Overview of the 18 CDR effect categories in the literature-based taxonomy with identifiers

Category	Description of CDR effect category irrespective of effect direction
Energy (A1)	The deployment of several CDR options has implications for the energy sector. This includes changes to energy supply and demand as well as impacts on energy independence and energy resource depletion[53–55].
Food & Yield (A2)	Implications for agricultural productivity are described for several CDR options—often driven by land use changes. Changes in yields impact competition over food, food prices, food security, and hunger. Impacts on agricultural exports and supply chains are also described in the literature[26,40,56,57].
Land use (A3)	Several CDR options demand substantial amounts of land. This land demand can lead to land use conflicts and indirect land use change[27,58,59]. The land demand of several CDR options has implications for multiple other identified categories, such as food and yield or biodiversity.
Markets & Prices (A4)	The deployment or availability of CDR could influence GDP growth, electricity prices, marginal abatement costs, or carbon price development[60,61]. Livelihoods can be affected due to altered income opportunities and workforce competition, work conditions, and overall economic prosperity[62,63].
Air quality & condition (B1)	Some CDR options influence air quality and their condition, e.g., by changing particulate matter and photochemical ozone formation or carbon monoxide emissions with direct impacts on human health[53,64–66]. One study also described distortions of winds as well as changes to air pressure and planetary boundary layer depth as potential side effects[67].
Biodiversity (B2)	CDR impacts on biodiversity have been described for various indicators such as abundance and diversity, survival and growth rates of various animal and plant species or microorganisms, as well as habitat implications. Both aggregated and highly specific cases of biodiversity impacts of CDR were found[28,39,68,69].
Heavy metals (B3)	CDR deployment can impact the natural cycling of a variety of toxic and non-toxic heavy metals as well as their industrial demand for CDR implementation. Changes to heavy metal leaching and abundance in soils, plants, and foods are documented in the literature[54,70,71]. The implications for heavy metals thematically overlap with other identified categories, such as changes to soil conditions or the water cycle.
Nutrients & Minerals (B4)	Impacts on the flow and demand of nutrients and minerals such as nitrogen, phosphorus, potassium, and related compounds are widely discussed. Some CDR options influence nutrient and mineral stocks in plants and soils and alter their leaching into freshwater. Implications for marine, freshwater, and terrestrial eutrophication are also documented[32,34,70,72]. Impacts on nutrients and minerals thematically overlap with other effect categories in this analysis, such as changes to the soil conditions or the water cycle.
pH change (B5)	Some CDR options can alter marine, terrestrial, or freshwater pH and, therefore, potential acidification, e.g., in ocean surface water, soils, or drainage water[32,35,73]. The identified pH changes are closely related to the soil conditions and the water cycle.
Raw materials (B6)	CDR-related changes to resource use and demand include a variety of materials such as different biomass types as feedstocks, sorbents, and silicates or different construction materials, including cement, steel, sand, and clay[54,74].
Soil condition (B7)	Some CDR options impact soils, e.g., compaction and composition, as well as their cation exchange capacity and electrical conductivity[30,75]. The formation of soil macroaggregates, gas exchange, soil temperature, and overall soil resilience can also be influenced by CDR[76,77]. This effect category thematically overlaps with other effect categories in this analysis, namely pH change, water cycle, heavy metals, as well as nutrients and minerals.
Toxicity & Radiation (B8)	Marine, freshwater, and terrestrial ecotoxicity, as well as human toxicity, are relevant considerations for CDR deployment, e.g., regarding ionizing radiation, stratospheric ozone depletion, or the leaching of polycyclic aromatic hydrocarbons[32,65,78]. Carcinogenic and non-carcinogenic human health impacts are relevant in this context[53,70,73].
Water cycle (B9)	Various water-related side effects of CDR are described in the literature, including changes to surface and groundwater quality and demand and, therefore, impacts on water scarcity. Some CDR options influence evapotranspiration, cloud formation, and precipitation patterns[25,79,80]. Structural changes in the environment can impact drainage and runoff with implications for flood protection[27,81]. This effect category thematically overlaps with other categories, namely pH change and soil condition, as well as nutrients and minerals.
Acceptance (C1)	Lacking support poses a potential implementation challenge for CDR. The literature describes insights into the general public perception of CDR but also the sentiments of direct stakeholders such as local communities, farmers, or landowners. The perception of CDR is influenced by a variety of factors, including perceived risks and benefits, legal aspects, as well as political and cultural beliefs[41,66,82,83].
Efficacy threats (C2)	An array of threats to successful CDR deployment were identified. Stored carbon may leak for various reasons, such as unintended natural sink disturbances, transportation, and geological storage leakages, non-climatic extreme events, climate shocks, sabotage, or human error. Removal rates can be reduced by sink saturation, climate-induced changes to biome productivity, indirect land use emissions, or a release of stored heat and CO_2 from the oceans when returning from an overshoot[62,84]. The unclear readiness and competitiveness of CDR options, related accounting mechanisms, as well as removal markets and industries pose further threats[36,85–87]. Efficacy threats thematically overlap with other identified implications, such as changes to albedo in the category of thermal impacts.
Non-CO_2 GHGs (C3)	While removing CO_2 from the atmosphere, CDR can also impact non-CO_2 greenhouse gas emissions primarily from soils, such as methane and nitrous oxide emissions[35,38,88]. However, deliberate atmospheric removal of non-CO_2 greenhouse gases is beyond the scope of this study.
Policy response (C4)	The expected large-scale availability of CDR could lead to reduced or delayed emission reductions, obscured acknowledgment of policy failure, and carbon debt—often discussed as 'moral hazard'[84,89]. Ethical questions of mitigation burden sharing in the context of power imbalances and contrary geopolitical interests, as well as concerns of a CDR-induced commodification of nature and active climate design, pose challenges for policymakers[90,91]. CDR policies can further conflict with other policy goals, such as the SDGs, or provide co-benefits to ease the implementation of non-climate policy goals[92].
Thermal impact (C5)	Beyond CO_2-related global warming, some CDR options impact global and local air, surface, and ocean temperatures in various ways. This includes modifications to surface and cloud albedo, emissivity, changes to local heat-island effects, atmospheric circulation, aerodynamic resistance, and overall heat and energy fluxes[24,93]. The temperature impact of CDR may also influence thaw-freeze cycles and, therefore, permafrost or arctic summer ice[94]. Thermal impacts thematically overlap with the water cycle in terms of evapotranspiration and cloud formation.

studies[24,25]. The land use impact of AR is described as negative in nine out of 11 articles.

BECCS: Impacts on land use, water cycle, and energy clearly dominate the considered literature body on BECCS side effects with still a comprehensive set of articles covering most other 15 effect categories—BECCS is the CDR option with the most available literature on side effects ($n = 72$). Effects on land use and the water cycle documented in the literature are predominately undesirable, while for energy, there are more studies ($n = 17$) indicating net energy production potential than studies ($n = 9$) indicating net energy demand for BECCS[26–29]. Many of the predominately negative effects on biodiversity, food, and yields, as well as nutrients and minerals, are related to the high land demand for bioenergy plantations for BECCS.

Biochar: Implications for food and yield, nutrients and minerals, and general soil conditions are the primarily discussed side effects of biochar soil amendment. Articles mentioning impacts on food and yield are predominantly positive ($n = 20$) compared to negative ($n = 5$) due to observed

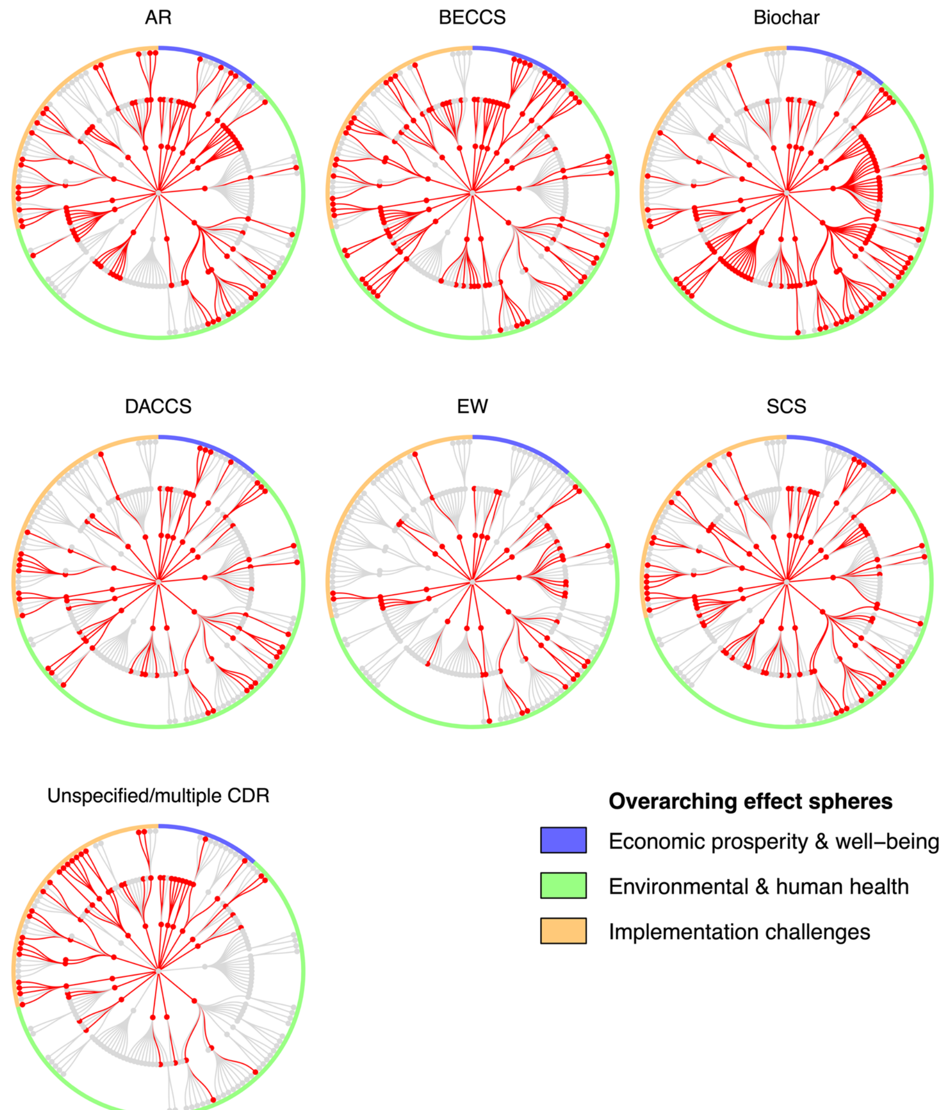

Fig. 3 | Effect profiles per considered CDR option based on the evaluated literature body. The layout position of effect categories and spheres is identical to Fig. 2. Red nodes and lines indicate that an effect category was present in the evaluated literature body for the respective CDR option; Gray nodes and lines indicate that an effect category was not present in the evaluated literature for the respective CDR option.

biochar-related yield increases for various crops[30,31]. Described implications for nutrients and minerals appear to be both positive and negative, with many effects for which desirability is unclear. The literature on soil effects of biochar is more positive ($n = 12$) than negative ($n = 5$), but many articles ($n = 10$) describe effects for which desirability is ambiguous or context-dependent and, therefore, unclear. The benefits of biochar described in the considered literature are the most manifold compared to the other CDR options in this study.

DACCS: Impacts on the water cycle, energy, acceptance, land use, and nutrients and minerals are the most discussed effect categories for DACCS. Articles on DACCS predominantly discuss undesirable side effects (19 out of 24 articles). The literature body also holds some information on desirable effects of DACCS deployment compared to respective baselines or counterfactual scenarios, e.g., reduced pressure on biodiversity or water and land demand[32,33], however, the number of articles is comparatively low ($n = 4$).

EW: Nutrients and minerals, acceptance, pH change, food and yield, and energy are the most discussed side effect categories for EW, while the evaluated literature evidence base on side effects of EW is the most limited ($n = 17$) among the considered CDR options. Positive effects of EW include the provision of essential nutrients and minerals such as phosphorus, potassium, calcium, and magnesium to soils and plants[34,35]. EW may also reduce soil acidification. The high energy demand for grinding rocks is described in several articles ($n = 4$) as a main drawback of this CDR option[35,36].

SCS: For SCS, impacts on nutrients and minerals, as well as on food and yield, are the most widely discussed side effects. Changes to general soil conditions, the water cycle, and biodiversity are also studied in several articles. Both positive and negative effects on the abundance of nutrients and minerals such as nitrogen, potassium, phosphorus, and related compounds in soils and their leaching are described, with a substantial set of effects for which the desirability is unclear[37,38]. More articles report benefits ($n = 10$) than downsides ($n = 5$) for food and yield due to observed yield increases for a variety of agricultural products, including maize, soybeans, and tomatoes[39,40]. Similar to biochar, the positive effects of SCS predominate for the majority of the effect categories considered, based on the evaluated literature.

Unspecific CDR: The reviewed articles on side effects of option-unspecific or aggregated CDR strongly focus on implications for policy response followed by information on biodiversity impacts and acceptance. Overall, the side effect information for unspecific CDR is dominated by undesirable effects. An array of different negative policy developments to the availability of CDR, including reduced and delayed climate action or issues of burden sharing[36,41], is described, as already laid out in detail in the previous section.

Fig. 4 | Evidence on the desirability of effects per category for the considered CDR options. Where available, information on the desirability of effects was directly taken from the respective articles. Otherwise, effect desirability was assigned manually as long as desirability was unambiguous and not strongly context-dependent. More information on the study's approach is provided in the Methods section. **a** shows the share of articles mentioning positive versus negative effects per effect category and CDR option. **b** shows the number of articles per mentioned effect desirability. Effect desirability is not aggregated within or across articles. Thus, double counting of articles is possible if articles mention multiple different effect desirabilities per effect category and CDR option.

The evaluation of effect desirability shows comparatively comprehensive literature evidence for positive effects for biochar and SCS across most effect categories. For BECCS, DACCS, and option-unspecific CDR, available information for the 18 evaluated effect categories appears to be more negative than positive in most cases. The number of articles covering positive versus negative side effects of AR appears to be balanced—for EW, the evidence on side effects is relatively scarce.

The general and CDR option-specific information on side effects can be complemented by looking at the geographical coverage of the evaluated literature (Fig. 5). There is substantial research on CDR side effects in Europe ($n = 58$) despite the continent's comparatively small size, while few studies on CDR side effects in Africa ($n = 13$), Oceania ($n = 13$), and South America ($n = 11$) have been identified. The few available studies for these three regions predominately discuss negative aspects—for at least 50% of the considered effect categories, there is no literature evidence on desirable effects. A large part of the available literature covers a global or multi-regional scope. For all regions considered, there is a predominance of articles describing negative effects compared to positive ones. Available information on CDR benefits is especially rich for Asia and Europe. For Africa, there is no evidence for DACCS, EW, and option-unspecific CDR in the evaluated evidence base. No articles studying SCS implications in South America were found. For all other regions, there is information on potential side effects for all considered CDR options. Interestingly, the evidence on benefits appears to be more constrained to individual regions than the evidence on disbenefits for DACCS, EW, and option-unspecific CDR.

Discussion and outlook

The presented taxonomy of CDR side effects, the comparison of effect profiles for the considered options, and the evaluation of available evidence on benefits versus disbenefits, including geographic differences, provide a comprehensive overview and map of the diverse and rapidly growing literature evidence on CDR implications. Our inventory of nearly 400 partly interrelated side effects underlines the multi-layered and complex nature of CDR as a climate change mitigation option. The diversity in CDR effect profiles and the perceived parallel existence of benefits and disbenefits across several CDR options indicate the potential to optimize climate change mitigation strategies and portfolios to foster advantages and minimize risks[42]. Our literature-based taxonomy of CDR side effects can be an initial but seminal tool for future studies to efficiently and comprehensively enhance knowledge on individual aspects of CDR implications and thus help close remaining research gaps. For policy-making, our map provides an overview of the various aspects that need to be carefully considered in the context of national and international CDR legislation and regulation. Below, we discuss current limitations as well as entry points for future extensions and opportunities for impactful analyses.

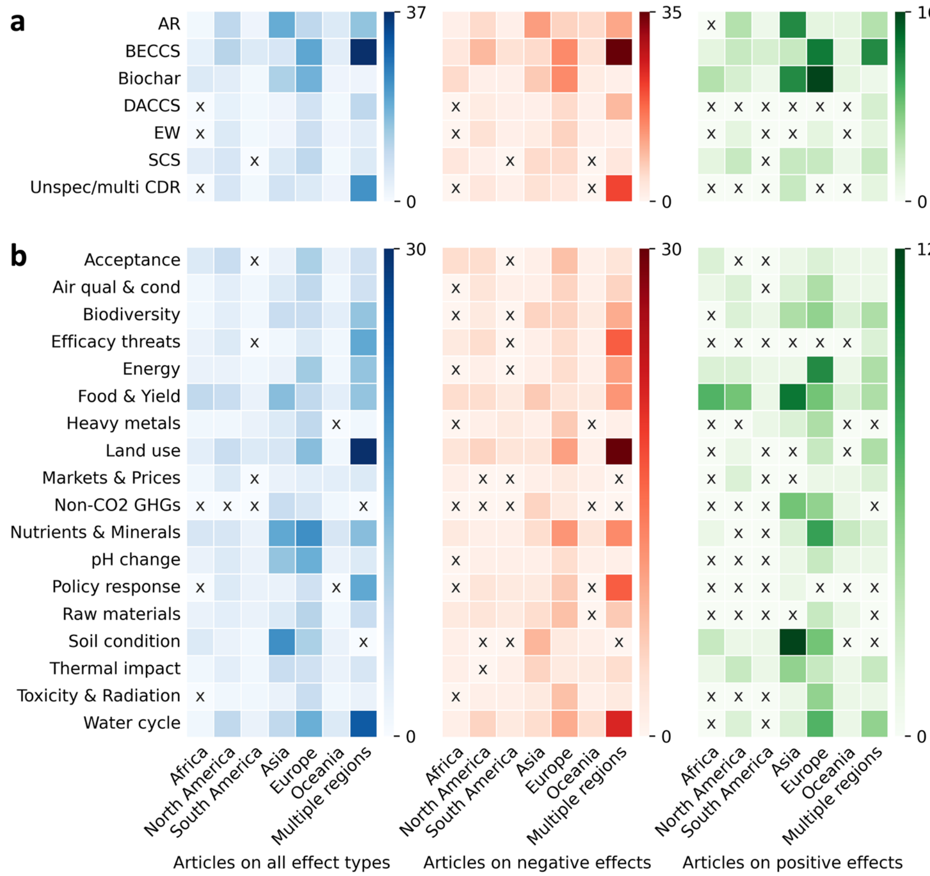

Fig. 5 | Number of articles mentioning side effects per CDR option and effect categories for different world regions. **a** shows the number of articles per CDR option and world region across all effect categories. **b** shows the number of articles per effect category and world region across all CDR options. "Multiple regions" refers to geographical study scopes covering more than one of the six listed continents—details are provided in the Supplementary Note 2. Studies without information on geographical scope were not considered in this figure. Double counting of articles is possible if articles mention multiple different effect desirabilities per region and effect category or CDR option. The blue column in (**a**, **b**) on all effect types also contains studies on effects with unclear or neutral desirability. Crossed cells indicate that no information is available in the evaluated evidence base.

Limitations

While taking a comprehensive and systematic approach to scan for evidence, the findings presented here are, by design, constrained by the currently available peer-reviewed literature. This study synthesizes the evidence on CDR side effects that were found and discussed by recent studies across different geographic contexts, suggesting a structured taxonomy for further analysis and highlighting where evidence is comparatively comprehensive or scarce. However, this reviewed literature might not yet be a complete representation of all potential effects and their desirability—categories might evolve as new evidence arises.

The search for recent CDR studies was as broad as possible, yet the selected body exclusively consists of articles where side effects of CDR were explicitly framed as such. While for the refined literature selection and full-text analysis, both explicit and implicit side effects of CDR were considered, the initial literature identification was restricted to articles written in English and explicitly articulating side effects or phenomena hampering successful CDR deployment in their title, abstract, or keywords (see Methods and Supplementary Table 1 for details on the applied side effect identification). Evidence that uses a different vocabulary or language to discuss CDR side effects might thus have been missed. Furthermore, only articles that consider side effects in an explicit CDR context have been considered. Articles that deal with CDR components or options in non-CDR contexts, such as afforestation as a nature-based solution or bioenergy without CCS as an energy source, were not considered. This more focused approach is meaningful, as many side effects of the considered CDR options are setup-specific. However, there may be several side effects that have not been discussed in an explicit CDR context but would also occur when a specific CDR option is deployed.

The focus on original research articles published since 2018 allowed for a more in-depth evaluation of the individual full-texts on up-to-date effects; however, it excluded side effect literature that was published before. To evaluate potential blind spots, the inventory of side effects of this study was compared to the CDR side effects described in other review articles and the IPCC AR6 report[16–22,43]. Potential implications for non-CO_2 emissions are mentioned for AR[19] and BECCS[17,18] in previous reviews, which were not covered in our literature-based inventory. For biochar, ref. 17. mention policy implications concerning potential competition over biomass resources, which is also not part of our literature body. Apart from this, we conclude that despite the restriction to articles published after 2018, the vast majority of effect categories per CDR mentioned in other reviews is comprehensively covered and, in many cases, further detailed by our study. However, modifying the set of considered research articles would likely have an impact on the evaluation of effect desirability in terms of the distribution between articles discussing positive versus negative effects—especially for CDR options where the available evidence is comparatively scarce.

There are also limitations induced by the assessment of the identified literature. The evaluated articles are very heterogeneous. They differ in terms of methodological approaches, considered CDR deployment volumes, effect sizes, effect baselines, and CDR intervention contexts with various temporal and geographical scopes. Furthermore, effect desirability is determined in comparison to an associated baseline or counterfactual scenarios defined within the context and scope of a respective study, which might make wider comparability challenging. Our approach allowed for an integration of a wide range of different study designs, including IAM modeling, LCAs, small to medium-scale field experiments, surveys, as well as conceptual works (Fig. 1b). This resulted in a rich evidence base and provided an overall picture of the diverse CDR side effects and their current academic discussion. However, the current approach does not yet allow for a comparison of the sizes or significance of identified benefits and disbenefits.

The way forward

The proposed taxonomy and effect profiles of studies per CDR option allow to identify key gaps in the literature. For example, several theoretically relevant side effect categories are not extensively covered in the evaluated literature for BECCS. These gaps are apparent in direct comparison to AR, for which there is comprehensive information on albedo changes or impacts on soil composition and quality, while for the bioenergy plantations that are integral to BECCS, this is not the case despite expected effect similarities. Importantly, for bioenergy production without CCS, the literature body for the two mentioned effect categories is much larger[44–46], which partly links to limitations discussed in the previous section but also to challenges that need to be overcome when synthesizing evidence on complex CDR options. Similarly, impacts on non-CO_2 greenhouse gas emissions from soils are discussed in several articles on biochar and SCS, while there is little information in the evidence base of recent literature for AR, BECCS, and EW even though these three options also actively influence soils, as previous reviews highlighted[17–19]. These differences in literature coverage, despite similarities in the expected effects, indicate potential research gaps. Generally, the here presented effect profiles per CDR option may support future investigations to evaluate whether missing information on certain effect categories points to their non-existence in the real world or only in the literature.

Our map identifies clear gaps in geographical coverage. Comparatively few studies focus explicitly on CDR side effects in Africa, South America, and Oceania, while there is substantial evidence of side effects in Europe, Asia, and on a global or multi-regional basis. This insight is also supported by recent findings on literature coverage on CDR in general[15]. This underrepresentation of Africa and South America is critical as these regions are considered essential for CDR deployment in mitigation pathways in IAMs[15,23,47] and, therefore, require urgent further investigation. This is especially the case since the few available studies for these regions mostly highlight negative aspects. Our analysis does not allow to identify a clear reason for these regions' underrepresentation.

Interlinkages and overlaps between side effect categories, observed throughout conducting this study, were highlighted in part in Table 1, e.g., for land use and biodiversity or soil conditions and the water cycle. While beyond the scope of this study, a more systematic analysis of such effect chains and feedbacks could further enhance the understanding of CDR implications and potentially feed into further extensions of the here presented taxonomy.

The comparison and evaluation of implications of different CDR options would further benefit from systematic reviews of the evidence on effect sizes and has already been started to some degree[16]. Our map and taxonomy can provide guidance for determining effect categories and related evidence as entry points for more comprehensive effect quantifications. Several side effects, such as pH change or nutrient cycling, may have optimal ranges, where benefits may be turned into disbenefits and vice versa, depending on whether effect sizes are within the optimal range or not. This is highly context and option-setup-dependent and has implications for sustainable CDR potentials, which warrants further analysis.

Ultimately, we hope this evidence map and taxonomy will facilitate more comprehensive and consistent analyses of CDR side effects to ensure an evidence-based integration in mitigation strategies and CDR portfolios that minimize disbenefits and maximize benefits.

Methods

This systematic map of CDR side effects consists of four main methodological steps, namely, literature identification, literature selection, literature coding, and literature synthesis. The individual steps are detailed below.

Literature identification

Potentially relevant peer-reviewed literature on CDR for this study was systematically identified via the abstract and citation database Scopus, using one keyword-based search query per considered CDR option and an additional query for unspecific CDR as a general mitigation concept. The developed search queries were partly informed by the queries used in the review and map by ref. 17, and ref. 48. The CDR queries were combined with additional subqueries to restrict the selection to articles explicitly discussing positive or negative side effects of CDR, as well as potential threats to CDR deployment. The queries are presented in Supplementary Table 1. By the time the queries were applied (May 20, 2022), 14,704 individual articles were identified.

Literature selection

Not all literature resulting from the search queries was indeed relevant to this study. For the literature selection, we used a machine-learning-assisted selection process to separate relevant from irrelevant studies. To ensure consistency and transparency, first, a set of inclusion and exclusion criteria for selecting relevant studies was developed (Supplementary Table 2).

Based on the inclusion and exclusion criteria, a random sample ($n = 1010$) of the potentially relevant literature ($n = 14{,}704$) was manually labeled as relevant or irrelevant based on titles, abstracts, and keywords, making use of the NACSOS platform[49]. The labeled subset was used to train a machine learning relevance classifier, which is made available. The classifier was used to predict the relevance of the unseen literature. The prediction scores allowed us to sort the remaining literature in descending order of predicted relevance for the further screening process. The sorted unseen literature was screened by hand and iteratively tested if a recall target of 95% with $p < 0.05$ was met, using the stopping criterion developed by ref. 50. The statistical stopping criterion was met after screening 7714 documents, which allowed for around 50% work-saving—982 truly relevant articles were identified.

The selection was further restricted to original research articles (no review articles) and limited to publications since 2018 to focus on the most recent developments and literature evidence on CDR side effects since the comprehensive review on CDR side effects by ref. 17.—importantly, more than 50% of all relevant articles were published in or after 2018. The full list of articles labeled relevant, including their study type (see Data availability statement), as well as a PRISMA-aligned[51] flow chart (Supplementary Fig. 1) of the literature identification and selection process, are made available[52].

Literature coding

Before selected full-texts were systematically reviewed and coded, each selected document was critically re-evaluated to ensure that all requirements of the defined inclusion criteria were also met based on the full-text and that no labeling errors had occurred. Eventually, 233 articles were considered in the evidence synthesis. For each considered full-text, all quantitative and qualitative information on side effects was extracted and systematically documented, following coding guidelines developed for this purpose. The coding guidelines are made available in the Supplementary Note 2.

Literature synthesis

To develop a literature-based taxonomy of CDR side effects, all identified effects and implications were manually grouped into categories and subcategories based on thematic similarities and differences. This was done in an iterative process to continuously refine the categories. Based on the identified categories and subcategories, the literature-based effect profiles of the six CDR options were compared.

The quantitative and qualitative literature evidence per side effect of the considered CDR options was also evaluated concerning effect desirability, meaning whether side effects are associated with societal, environmental, and economic benefits or disbenefits. Where no explicit information on effect desirability was provided in the evaluated articles, desirability was assigned in comparison to the articles' respective effect baselines, given that desirability was unambiguous and not strongly context-dependent. For example, described increases in energy generation through BECCS were considered unambiguously desirable, while the desirability of described soil pH changes was more unclear and thus not manually determined, as different regions, land uses, or soil types have various optimal pH ranges. A complete list of coded side effects with related effect groups and effect desirability is made available in the ZENODO repository corresponding to this study. Extracted information on the geographical scopes of the articles in the evidence base was used to evaluate regional differences in the literature coverage. Code for processing and visualizing the data is made available.

Data availability

The literature-based data set underlying this study is made available at: [https://doi.org/10.5281/zenodo.10822108].

Code availability

The code for the machine learning classifier, as well as for processing and visualizing the data, is made available at: [https://doi.org/10.5281/zenodo.10822108].

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Author contributions
R.P., S.F., and J.R. conceptualized the study; R.P., S.F., S.L., and J.R. devised the methodology; R.P., S.L., L.S., and S.F. worked on the literature identification, selection, and coding; R.P. and J.R. prepared the visualizations; R.P. wrote the original draft; and all authors reviewed and edited the paper.

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